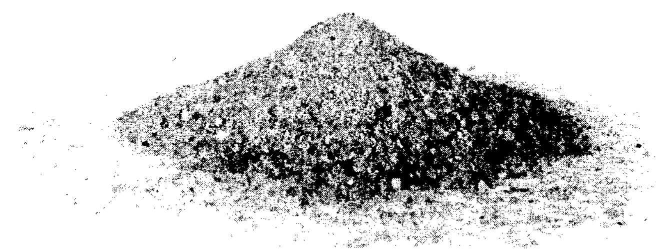
Ubiquity

WHY CATASTROPHES HAPPEN



MARK BUCHANAN

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Politics is not the art of the possible.
It consists in choosing between
the disastrous and the unpalatable.

—**JOHN KENNETH GALBRAITH**[1]

History is the science
of things which are never repeated.

—**PAUL VALÉRY**[2]

✦

IT WAS 11 A.M. ON A FINE SUMMER MORNING IN SARAJEVO, JUNE 28, 1914, when the driver of an automobile carrying two passengers made a wrong turn. The car was not supposed to leave the main street, and yet it did, pulling up into a narrow passageway with no escape. It was an unremarkable mistake, easy enough to make in the crowded, dusty streets. But this mistake, made on this day and by this driver, would disrupt hundreds of millions of lives, and alter the course of world history.

The automobile stopped directly in front of a nineteen-year-old Bosnian Serb student, Gavrilo Princip. A member of the Serbian terrorist organization Black Hand, Princip couldn't believe his luck. Striding forward, he reached the carriage. He drew a small pistol from his pocket. Pointed it. Pulled the trigger twice. Within thirty minutes, the Austro-Hungarian Archduke Franz Ferdinand and his wife Sophie, the carriage's passengers, were dead. Within hours, the political fabric of Europe had begun to unravel.

In the days that followed, Austria used the assassination as an excuse to begin planning an invasion of Serbia. Russia guaranteed protection to the Serbs, while Germany, in turn, offered to intercede on Austria's behalf should Russia become involved. Within just thirty days, this chain reaction of international threats and promises had mobilized vast armies and tied Austria, Russia, Germany, France, Britain, and Turkey into a deadly knot. When the First World War ended five years later, ten million lay dead. Europe fell into an uncomfortable quiet that lasted twenty years, and then the Second World War claimed another thirty million. In just three decades, the world had suffered two engulfing cataclysms. Why? Was it all due to a chauffeur's mistake?

On the matter of the causes and origins of the First World War, of course, almost nothing has been left unsaid. If Princip touched things off, to the British historian A.J.P. Taylor the war was really the consequence of railway timetables, which locked nations into a sequence of military preparations and war declarations from which there was no escape. The belligerent states, as he saw it, "were trapped by the ingenuity of their preparations."[3] Other historians point simply to German aggression and national desire for expansion, and suggest that the war was inevitable once Germany had become unified under Bismarck a half century earlier. The number of specific causes proposed is not much smaller than the number of historians who have considered the issue, and even today major new works on the topic appear frequently.[4] It is worth keeping in mind, of course, that all this historical "explanation" has arrived well *after* the fact.

In considering how well we understand the natural rhythms of human history, and in judging how able we are nowadays to perceive even the rough outlines of the future, it is also worth remembering that the century preceding 1914 had been like a long peaceful afternoon in European history, and that to historians of the time the wars seemed to erupt like terrifying and inexplicable storms in a cloudless sky. "All the spawn of hell," the American historian Clarence Alvord wrote after the First World War, "roamed at will over the world and made of it a shambles. . . . The pretty edifice of . . . history, which had been designed and built by my contemporaries, was rent asunder. . . . The meaning we historians had read into history was false, cruelly false."[5] Alvord and other historians thought they had discerned legitimate patterns in the past, and had convinced themselves that modern human history would unfold gradually along more or less rational lines. Instead, the future seemed to lie in the hands of bewildering, even malicious forces, preparing unimaginable catastrophes in the dark.

The First World War, the war sparked by "the most famous wrong turning in history,"[6] is the archetypal example of an unanticipated upheaval in world history, and one might optimistically suppose that such an exceptional case is never likely to be repeated. With the aid of hindsight, many historians now believe they understand the larger forces that caused the world wars of the twentieth century, and that we can once again see ahead with clear vision. But Alvord and his colleagues had similar confidence a century ago. What's more, few of us—professional historians included—seem any wiser when it comes to the present.

In the mid-1980s, the Union of Soviet Socialist Republics had existed for nearly three-quarters of a century, and it stood as a seemingly permanent fixture on the world stage. At that time, there were palpable fears in the United States that the U.S.S.R. was way ahead militarily, and that only with a concerted effort could the United States even stay competitive. In 1987, one would have had to scour the journals of history and political science to find even a tentative suggestion that the U.S.S.R. might collapse within half a century, let alone in the coming decade. Then, to everyone's amazement, the unthinkable became a reality—in just a few years.

In the wake of the U.S.S.R.'s unraveling, some historians leaped to another conclusion. Democracy seemed to be spreading over the globe, binding it up into one peaceful and lasting New World Order—the phrase favored, at least, by politicians in the West, who happily proclaimed the final victory of democracy (and capitalism) over communism. Some writers even speculated that we might be approaching "the end of history,"[7] as the world seemed to be settling into some ultimate equilibrium of global democracy, the end result of a centuries-long struggle for the realization of a deep human longing for individual dignity. Just a few years later, in what was then Yugoslavia, war and terrible inhumanity once again visited Europe. A momentary setback? Or the first ominous sign of things to come?

No doubt historians can also explain quite convincingly—though in retrospect, of course—why these events unfolded as they did. And there is nothing wrong with this kind of explanation; it is in the very nature of history that thinking and explanation must always proceed backwards. "Life is understood backwards," as Søren Kierkegaard once expressed the dilemma, "but must be lived forwards." And yet this need to resort always to explanations *after the fact* also underlines the seeming lack of any simple and understandable patterns in human affairs. In human history, the next dramatic episode, the next great upheaval, seems always to be lurking just around the corner. So despite their aim to find at least some meaningful patterns in history, it is probably true that many historians sympathize with the historian H. A. L. Fisher, who in 1935 concluded:

> Men wiser and more learned than I have discerned in history a plot, a rhythm, a predetermined pattern. These harmonies are concealed from me. I can see only one emergency following upon another . . . and only one safe rule for the historian: that he should recognize in the development of human destinies the play of the contingent and the unforeseen. . . . The ground gained by one generation may be lost by the next.[8]

Having read this far, you may be surprised to learn that this book is about ideas that find their origin not in history but in theoretical physics. It may seem decidedly odd that I have begun by recounting the beginning of the last century's major wars, and by trumpeting the capricious and convulsive character of human history. There is nothing new in the recognition that history follows tortuous paths, and that it has forever made a mockery of attempts to predict its course. My aim, however, is to convince you that we live in a special time, and that new ideas with a very unusual origin are beginning to make it possible to see *why* history is like it is; to see *why* it is and even must

be punctuated by dramatic, unpredictable upheavals; and to see *why* all past efforts to perceive cycles, progressions, and understandable patterns of change in history have necessarily been doomed to failure.

A Faulty Peace

One may suspect that human history defies understanding because it depends on the unfathomable actions of human beings. Multiply individual unpredictability a billion times, and it is little wonder that there are no simple laws for history—nothing like Newton's laws, for instance, that might permit the historian to predict the course of the future. This conclusion seems plausible, and yet one should think carefully before leaping to it. If human history is subject to unpredictable upheavals, if its course is routinely and drastically altered by even the least significant of events, this does not make it unique as a process. In our world, these characteristics are ubiquitous, and it is just dawning on a few minds that there are very deep reasons for this.

The city of Kōbe is one of the gems of modern Japan. It lies along the southern edge of the largest Japanese island of Honshū, and from there its seaport—the world's sixth largest—handles each year nearly a third of all Japan's import and export trade. Kōbe has excellent schools, and its residents bask in what seems to be a haven of environmental stability. The city has good reason to call itself an "urban resort":[9] peaceful sunrises have for centuries given way to bright, warm afternoons, which have in turn slipped into cool, tranquil evenings. If visiting Kōbe, you would never guess that just beneath your feet invisible forces were preparing to unleash unimaginable violence. Unless, of course, you happened to be there at 5:45 A.M., January 17, 1995, when the calm suddenly fell to pieces.

At that moment, at a location just off the Japanese mainland, twenty kilometers southwest of Kōbe, a few small pieces of rock in the ocean floor suddenly crumbled. In itself, this was unremarkable; minor rearrangements of the Earth's crust happen every day in response to the stresses that build up slowly as continental plates, creeping over the planet's surface, rub against one another. But this time, what started as a minor rearrangement did not end up that way. The crumbling of those first few rocks altered the stresses on others nearby, causing them also to break apart. Farther down the line, still others followed suit, and in just fifteen seconds the earth ripped apart along a line some fifty kilometers long. The resulting earthquake shook the ground with the energy of a hundred nuclear bombs, ruining every major road or rail link near Kōbe and, in the city itself, causing more than a hundred thousand buildings to tilt or collapse. It sparked raging fires that took a week to control, and rendered inoperable all but 9 of the 186 berths in Kōbe's port. Ultimately, the devastation killed five thousand people, injured thirty thousand, and left three hundred thousand homeless.[10]

For centuries the area around Kōbe had been geologically quiet. Then, in just a few seconds, it exploded. Why?

Japan is known for its earthquakes. A quake releasing ten times as much energy leveled the city of Nobi in central Japan in 1891, and others struck in 1927, 1943, and 1948 at other locations. The intervals between these great earthquakes—thirty-five, sixteen, and five years—hardly form a simple, predictable sequence, as is typical of earthquakes everywhere. If the historian H. A. L. Fisher failed to see in history "a plot, a rhythm, a predetermined pattern," then so too have geophysicists failed utterly, despite immense effort, to discern any simple pattern in the Earth's seismic activity.

Modern scientists can chart the motions of distant comets or asteroids with stunning precision, yet something about the workings of the Earth makes predicting earthquakes extremely difficult, if not altogether impossible. Like the fabric of international politics, the Earth's crust is subject to sporadic and seemingly inexplicable cataclysms.

The Great Burnout

Not far to the west of Wyoming's vast Bighorn Basin, the wild and unrestrained landscape of Yellowstone National Park climbs into the Rockies. Immense forests of aspen and lodgepole pine clothe the mountains like a soft fabric, hiding black bears and grizzlies, moose, elk, deer, and innumerable species of birds and squirrels, all thriving in the seemingly pristine wilderness. Here and there a great rocky dome bursts out of the pines and towers over the park like a timeless sentinel. This is America's most beautiful natural park, set aside for protection back in 1872, and now the holiday destination of more than a million visitors each year.

But if Yellowstone is a place of almost unfathomable peace, it is also, sporadically, a place of terrific, incendiary violence.

Lightning sparks several hundred fires within the park every year. Most burn less than an acre, or maybe a few acres before dying out, while others carry on to destroy a few hundred or, far more rarely, a few thousand. As of 1988, even the largest fire ever recorded, in 1886, had burned only twenty-five thousand acres. So late in June of 1988, when a lightning bolt from a summer thunderstorm sparked a small fire near Yellowstone's southern boundary, no one was unduly alarmed. The fire was named the Shoshone, and the Forest Service began monitoring its progression. Within a week, storms had ignited a couple of other fires elsewhere in the park, and yet there was still no cause for concern. On July 10, when a brief rain fell, there were a handful of fires still smoldering, but all seemed well in hand and likely to burn out in the coming weeks. It didn't happen that way.

Whether it was the unusually dry conditions or the persistent winds, no one can really say, but by the middle of July the fires had only become bigger. "Up until then, with the fires," a National Park Service spokeswoman later recalled, "it was business as usual."[11] But on July 14, a fire given the name Clover spread to forty-seven hundred acres, and another called the Fan grew to cover twenty-nine hundred acres. Four days later yet another fire, sparked in an area known as Mink Creek, had exploded to cover thirteen thousand acres, and forest managers were beginning to see things that no expert had envisaged. The Shoshone fire suddenly gathered new life, racing to consume more than thirty thousand acres in just a few days, and by August some two hundred thousand acres of the park either had burned or were burning; on all fronts flames were advancing five to ten miles each day under a smothering blanket of smoke ten miles high.

Over the next two months, more than ten thousand firefighters from across the country, using 117 aircraft and more than a hundred fire engines, struggled ineffectually as the blaze swept through the park. Eventually the flames consumed 1.5 million acres and more than $120 million in federal firefighting money, and lost momentum and dwindled only with the coming of the first snow in autumn. Somehow, from one or several insignificant bolts of lightning an unstoppable inferno had emerged that made the previous worst fire in the history of Yellowstone look like a backyard barbecue. What made this one so bad? And why didn't anyone see it coming?

A Sharp Turn South

On September 23, 1987, investors around the world picked up *The Wall Street Journal* to see a headline heralding still more fantastic news: STOCK PRICES SOAR IN HEAVY TRADING; INDUSTRIALS RISE RECORD 75.23 POINTS.[12] It had been an incredible summer, and with almost perfect regularity, each day and each week had brought higher numbers and easy profits. Several weeks earlier, prices on the New York Stock Exchange had reached a new all-time high, and though they had slipped a tiny bit since then, the surge of September 23 was exactly what most traders expected. It was the natural end of a minor "correction," and it set the stage for further gains. "In a

market like this," one trader said, "any news is good news. It's pretty much taken for granted now that the market is going to go up."[13]

So, two weeks later, when the market opened for trading on October 6, most analysts fully expected stock prices to climb even higher. When prices unexpectedly began to tumble, there was at first little concern. It was obvious to most analysts that this was merely another insignificant correction, a temporary setback caused by investors' uncertainty about interest rates or the value of the dollar. But for some reason this tiny correction took hold. By the end of the day, a sudden rash of selling had treated the market's optimistic "bulls" to a sharp rap on the nose. As one remarked,

> This one really came out of the blue. I didn't expect it to be so bad. . . . we froze around 3 P.M. and just started watching the screens. Even the phones stopped ringing. We were watching history in the making.[14]

Even so, the historical drama had really only begun.

Reassuringly, the press quickly pointed out that the drop of October 6, if considered in historical context, wasn't even one of the hundred largest in percentage terms. So it wasn't really all that serious. The market continued to slide over the next week, and then October 14, 15, and 16 saw three considerable losses in a row. Still, as traders left New York City for the weekend, they were reading a *Wall Street Journal* that remained stoutly confident and hopeful:

> It was the third major decline in as many days. But several technical analysts said that the big volume accompanying Friday's session might mean better things ahead.

In fact, it meant something rather more ominous.

Over that weekend, in the minds and hearts of thousands of major investors, the subtle apprehensions that had been accumulating over the previous weeks precipitated into a torrential rain of fear. On Black Monday, October 19, when the exchange opened for trading at 9:30 A.M., it was immediately swept away in a mad panic: prices began to plummet. The rush to sell was so overwhelming that, by late afternoon, the outstanding value of stocks and bonds had been clipped by more than one-fifth, and some $500 billion had been erased from investors' financial statements. At close, a nightmarish gloom settled over Wall Street as traders contemplated the largest single-day free fall in market history. "It felt like the end of the world," wrote *Newsweek*, "after two generations of assurances that it couldn't possibly happen." The crash was nearly twice as severe as the infamous stock market collapse of 1929, although this time, fortunately, it didn't trigger a global economic depression. "It was God tapping us on the shoulder," one billionaire investor concluded, "a warning to get our act together."

As with the First World War or the great quake in Kōbe, no one had predicted the crash. Immediately *afterward*, on the other hand, analysts produced all kinds of dubious explanations for why it had happened when it did. Even today, however, there is little consensus. As a longtime Wall Street analyst has recently concluded,

> The crash of 1987 was such a storm of mass emotion that "market as machine" theorists worked overtime explaining the drop and figuring out how to "fix" the system. The theory that gained the most credence was that the crash was caused by so-called portfolio insurance computer programs, which in essence sold stocks as the market went lower. . . . Unfortunately for the theory, it does not explain very well why markets around the world crashed simultaneously or why the decline stopped. It is at an utter loss to explain why many indexes around the world that had no computer trading fell further than the Dow Jones Industrial Index. It also ignores the fact that throughout 1986 and 1987, market observers in an equally serious tone had continually explained why a stock market crash was impossible because of "safeguards that are in place," safeguards such as portfolio insurance.[15]

On a Sharp Edge

The roots of war are to be sought in politics and history, those of earthquakes in geophysics, of forest fires in patterns of weather and in the natural ecology, and those of market crashes in the principles of finance, economics, and the psychology of human behavior. Beyond the labels "disaster" and "upheaval," each of these events erupted from the soil of its own peculiar setting. Still, there is an intriguing similarity. In each case, it seems, the organization of the system—the web of international relations, the fabric of the forests or of the Earth's crust, or the network of linked expectations and trading perspectives of investors—made it possible for a small shock to trigger a response out of all proportion to itself. It is as if these systems had been poised on some knife-edge of instability, merely waiting to be "set off."

In the history of life, we find a similar pattern. The fossil record reveals that the number of species on our planet has—roughly speaking—grown steadily over the past six hundred million years. Yet on at least five separate occasions, sudden and terrible mass extinctions nearly wiped out every living thing. What happened? Many scientists point to precipitous changes in the Earth's climate, caused perhaps by the impact of large asteroids or comets. Others suggest that the extinction of just a single species can, on occasion, trigger others, which in turn cause still others, leading to an avalanche of extinctions that can consume large fractions of entire ecosystems. The mass extinctions continue to mystify biologists and geologists, and yet one thing is clear: if the fabric of life seems resilient and largely in balance with itself, the truth is rather more unsettling. The global ecosystem is occasionally visited by abrupt episodes of collapse.

When I was in grade school, one of the dreaded tasks assigned by the geometry teacher was to determine if two triangles were *similar.* Here is a big triangle, she would say, and here is another much smaller triangle, oriented in a different way. Are they, aside from the irrelevant details of overall size and orientation, the same triangle? Put otherwise: If you can shrink or expand either triangle at will, turn the two over and rotate them in any way you like, can you make the one fit precisely over the other? If so, then the triangles are similar—if you understand the essential logic of one, its angles and the ratios of the lengths of its sides, then you also understand the other.

Three centuries ago, Isaac Newton sparked a scientific revolution by noticing another kind of similarity. His contemporaries must have been at first disbelieving, and later stunned, when he told them that an apple falls to the ground in precisely the same way as the Earth moves round the Sun. Newton saw that both Earth and apple fall into the single category of *things moving under the force of gravity.* Before Newton, happenings on Earth and in the Heavens were utterly incomparable. Afterward, the motions of an apple or an arrow, a satellite, or even an entire galaxy were seen as deeply similar—as mere instances of a single, deeper process.

"The art of being wise," the American philosopher and psychologist William James once wrote, "is the art of knowing what to overlook,"[16] and this book is about a terrific step along the scientific road of learning what to overlook. It is about the discovery of a profound similarity not between triangles or moving objects, but between the upheavals that affect our lives, and the ways in which the complicated networks in which they occur—economies, political systems, ecosystems, and so on—are naturally organized. We might add to our list dramatic changes in fashion or musical taste, episodes of social unrest, technological change, even great scientific revolutions.

As we shall see, the key to a unified understanding lies in the subtle and powerful concept of the *critical state,* an idea that appears to be central to the scientific understanding of many processes in which the notion of history plays a fundamental role.

History Matters

For centuries, physicists have sought to capture the fundamental laws of the universe in timeless and unchanging equations, such as those of quantum theory or relativity. While this project has been enormously successful, the ultimate simplicity of such equations points to a paradox: If the laws of physics are so simple, why is the world so complex? Why don't ecosystems, organisms, and economies reveal the same simplicity as Newton's laws and the other laws of physics?

In the late 1970s and 1980s, scientists discovered at least part of the answer—*chaos.* When a pinball scatters through a pinball machine, its path is extraordinarily sensitive to tiny influences along the way. This is chaos. Inside any ordinary balloon, the molecules also move according to the law of chaos: give a tiny nudge to just a single molecule, and in much less than a minute every last one will be affected. In the context of the Earth's atmosphere, chaos brings us the "butterfly effect," the incredible conclusion that the flapping of a butterfly's wings in Portugal now might just lead to the formation of a severe thunderstorm over Moscow in a couple of weeks' time.

So here we have one mechanism by which complexity can grow out of simplicity. Predicting the long-term future of any chaotic system is practically impossible, and a chaotic process looks wildly erratic even if the underlying rules are actually quite simple. Researchers have discovered chaos at work in the fluctuations of things ranging from lasers to rabbit populations, and in the late 1980s and early 1990s some scientists even hoped that chaos might finally make sense of the wild ups and downs of financial markets.

But it didn't, for there is an aspect of the world's complexity that chaos leaves completely untouched. Not its unpredictability, but its *upheavability*. Chaos is limited in its ability to explain tumultuous events, as researchers had hoped it might, because chaos in itself does not generate upheavals. Something more is needed if chaos is to give rise to tumultuous events, such as stock market crashes or earthquakes, and that something more is history.

To see why, think again about the famous butterfly example, but with one important difference: imagine that the butterfly is inside a balloon. A butterfly could flap its wings for eternity inside a balloon and never cause the equivalent of a thunderstorm in that enclosed space. This is because the air in the balloon lives in peace under unchanging conditions, in what scientists refer to as *equilibrium*. In equilibrium, it is certainly true that the individual molecules toss around in utter chaos, but that's pretty much the end of the story. No larger patterns ever emerge, nothing important ever happens, and so the idea of history has little meaning. For the air in the balloon, the past and the future are essentially the same. In contrast, the air in the Earth's atmosphere is very much out of equilibrium. Far from being left in peace, it is being continually stirred and agitated and energized by the influx of light from the Sun. The result is the rich and ever unfolding history of the weather and climate. Out of equilibrium, there is such a thing as history.

This gives us a clue about the cause of upheavability: it clearly has something to do with the way things work when out of equilibrium. For the most part, out-of-equilibrium physics remains a forest of the unknown. And yet, over the past two decades, scientists have forged a few remarkable insights, one of which casts the upheavals we met earlier in this chapter in a fascinating light. The key idea is the notion of the *critical state*, a special kind of organization characterized by a tendency toward sudden and tumultuous changes, an organization that seems to arise naturally under diverse conditions when a system gets pushed away from equilibrium. This is the first

landmark discovery in the emerging science of nonequilibrium physics—what we might equally well call the field of *historical physics*.

I should point out that in recent years this field has also gone under another name: complexity theory. After all, when things are out of equilibrium they tend to be complex—the intricately knitted structure of a food web, the irregular surface of a fractured brick, the infinitely detailed shape of a snowflake. But *history* reveals the essential element that underpins complexity in all these cases. You cannot understand either a food web or a snowflake by solving simple, timeless equations. Instead, you need to delve into the past and deal with a long, tortuous history carved out by what the biologist Francis Crick has termed "frozen accidents." If some species goes extinct, this leaves an unalterable mark on the food web forevermore. If at some instant a small bit of water freezes on one side of a growing snowflake rather than another, its future is likewise altered irreversibly. Such accidents, irreversible in their consequences and piling up one on the other, lead to the complexity we see around us.

But if complexity emerges out of strings of historical accidents, and there are no fundamental equations for things in which history matters, how can one achieve any scientific understanding? Scientists have recently found a way—by replacing equations with games. The physics research journals are now stuffed with papers about the workings of simple mathematical games: some meant to explore the basic historical process behind crystal growth, others to mimic that which lies behind the formation of rough surfaces, and so on. There are hundreds, each slightly different in its details, but all sharing a deeply historical nature. These games offer a way to proceed in the face of history and its messy strings of accidents. In effect, they permit scientists to greatly simplify the things they're studying, whether an economy or an ecosystem, and to focus on the fundamental processes at work without being distracted by myriad confusing details.

And of all these games, one stands out as a kind of archetype of simplicity, and has been central to the discovery of the underlying cause of a vast range of tumultuous events. To understand this "sandpile game," a focal point for our story, imagine dropping grains of sand one by one onto a table and watching the pile grow. A grain falls accidentally here or there, and then in time the pile grows over it, freezing it in place. Afterward, the pile feels forever more the influence of that grain being just where it is and not elsewhere. In this case, clearly, history matters, since what happens now can never be washed away, but affects the entire course of the future.

"All great deeds and all great thoughts," Albert Camus once wrote, "have ridiculous beginnings."[17] And so it was in 1987 when physicists Per Bak, Chao Tang, and Kurt Weisenfeld began playing this sandpile game in an office at Brookhaven National Laboratory, in New York State. As it turns out, this seemingly trivial game lies behind the discovery of the widespread importance of the critical state—the discovery that can help us to make sense of upheavals.

The Sand Men and the Critical State

Theoretical physicists enjoy posing seemingly trivial questions that, after a bit of thinking, turn out not to be so trivial. In this respect the sandpile game turned out to be a real winner. As grains pile up, it seems clear that a broad mountain of sand should edge slowly skyward, and yet things obviously cannot continue in this way. As the pile grows its sides become steeper, and it becomes more likely that the next falling grain will trigger an avalanche. Sand would then slide downhill to some flatter region below, making the mountain smaller, not bigger. As a result, the mountain should alternately grow and shrink, its jagged silhouette forever fluctuating.

Bak, Tang, and Weisenfeld wanted to understand those fluctuations: What is the typical rhythm of the growing and shrinking sandpile? Of course, they didn't really care about sandpiles. In studying this silly problem, they were really chasing some insights regarding

the general workings of nonequilibrium systems. The sandpile seemed like a nice, simple starting point, and with luck, they hoped, they might discover in this setting some patterns of behavior that would apply to a lot more than just sandpiles.

Unfortunately, dropping sand one grain at a time is a delicate and laborious business. So in seeking some answers concerning the rhythm of the pile's growth, Bak and his colleagues turned to the computer. They instructed it to drop imaginary "grains" onto an imaginary "table," with simple rules dictating how grains would topple downhill as the pile grew steeper. It was not quite the same as a real sandpile, and yet the computer had one spectacular advantage: a pile would grow in seconds rather than days. It was so easy to play the game that the three physicists soon became glued to their computer screens, obsessed with dropping grains and watching the results. And they began to see some curious things.

The first big surprise came as the answer to a simple question: What is the typical size of an avalanche? How big, that is, should you expect the very next avalanche to be? The researchers ran a huge number of tests, counting the grains in millions of avalanches in thousands of sandpiles, looking for the typical number involved. The result? Well . . . there was no result, for there simply was no "typical" avalanche. Some involved a single grain; others ten, a hundred, or a thousand. Still others were pile-wide cataclysms involving millions that brought nearly the whole mountain tumbling down. At any time, literally anything, it seemed, might be just about to happen.

Imagine wandering into the street, anticipating how tall the next person might be. If people's heights worked like these avalanches, then the next person might be less than an inch tall, or over a mile high. You might crush the next person like an insect before seeing him or her. Or imagine that the duration of your trips home from work went this way; you'd be unable to plan your life, since tomorrow evening's journey might take anything from a few seconds to a few years. This is a rather dramatic kind of unpredictability, to say the least.

To find out why it should show up in their sandpile game, Bak and colleagues next played a trick with their computer. Imagine peering down on the pile from above, and coloring it in according to its steepness. Where it is relatively flat and stable, color it green; where steep and, in avalanche terms, "ready to go," color it red. What do you see? They found that at the outset the pile looked mostly green, but that, as the pile grew, the green became infiltrated with ever more red. With more grains, the scattering of red danger spots grew until a dense skeleton of instability ran through the pile. Here then was a clue to its peculiar behavior: a grain falling on a red spot can, by dominolike action, cause sliding at other nearby red spots. If the red network was sparse, and all trouble spots were well isolated one from the other, then a single grain could have only limited repercussions. But when the red spots come to riddle the pile, the consequences of the next grain become fiendishly unpredictable. It might trigger only a few tumblings, or it might instead set off a cataclysmic chain reaction involving millions. The sandpile seemed to have configured itself into a hypersensitive and peculiarly unstable condition in which the next falling grain could trigger a response of any size whatsoever.

This may seem like something that only a physicist could find interesting. After all, in other settings, scientists have known about this condition for more than a century; they have referred to it technically as a critical state. But to physicists, it has always been seen as a kind of theoretical freak and sideshow, a devilishly unstable and unusual condition that arises only under the most exceptional circumstances—in liquids, for example, when held at precise temperatures and pressures under extraordinarily well controlled laboratory conditions. In the sandpile game, however, a critical state seemed to arise naturally and inevitably through the mindless sprinkling of grains.[18]

This led Bak, Tang, and Weisenfeld to ponder a provocative possibility: If the critical state arises so easily and inevitably in a simple computer model of a growing sandpile, might something like it also arise elsewhere? Despite what scientists had previously believed, might the critical state in fact be quite common? Could riddling lines of instability of a logically equivalent sort run through the Earth's crust, for example, through forests and ecosystems, and perhaps even through the somewhat more abstract "fabric" of our economies? Think of those first few crumbling rocks near Kōbe, or that first insignificant dip in prices that triggered the stock market crash of 1987. Might these have been "sand grains" acting at another level? Could the special organization of the critical state explain why the world at large seems so susceptible to unpredictable upheavals?

A decade of research by hundreds of other physicists has explored this question and taken the initial idea much further.[19] There are many subtleties and twists in the story to which we shall come later in this book, but the basic message, roughly speaking, is simple: The peculiar and exceptionally unstable organization of the critical state does indeed seem to be ubiquitous in our world. Researchers in the past few years have found its mathematical fingerprints in the workings of all the upheavals I've mentioned so far, as well as in the spreading of epidemics, the flaring of traffic jams, the patterns by which instructions trickle down from managers to workers in an office, and in many other things.[20] At the heart of our story, then, lies the discovery that networks of things of all kinds—atoms, molecules, species, people, and even ideas—have a marked tendency to organize themselves along similar lines. On the basis of this insight, scientists are finally beginning to fathom what lies behind tumultuous events of all sorts, and to see patterns at work where they have never seen them before.

Critical World?

So the ubiquity of the critical state might well be considered the first really solid discovery of complexity theory—or of what I have been calling historical physics. This is a discovery with implications, and not only for physicists and other scientists.[21] If the laws of physics didn't allow "frozen" accidents, the world would be in equilibrium, and everything would be like the gas in a balloon, resting forever in the same uniform and unchanging condition. But the laws of physics do allow events to have consequences that can become locked in place, and so alter the playing field on which the future unfolds. The laws of physics allow history to exist, and to play a crucial role in the way our world works. The discovery of the ubiquity of the critical state, then, is also the first deep discovery concerning the way that historical processes usually work, which brings us back to the point from which we started this chapter.

In principle, history could unfold far more predictably than it does. It needn't, in principle, be subject to terrific cataclysms of all sorts. One of our tasks in this book is to examine why the character of human history is as it is, and not otherwise. The answer, I suggest, is to be found in the critical state and in the new nonequilibrium science of games, which aims to study and categorize the kinds of historical processes that are *possible.* If many historians have searched for gradual trends or cycles as a way of finding meaning and making sense of history, then they were using the wrong tools. These notions arise in equilibrium physics and astronomy. The proper tools are to be found in nonequilibrium physics, which is specifically tuned to understanding things in which history matters.

In the very same year that Bak, Tang, and Weisenfeld invented their game, the historian Paul Kennedy published *The Rise and Fall of the Great Powers.*[22] In that book he laid out the idea that the large-scale historical rhythm of our world is determined by the natural buildup and release of stress in the global network of politics and

economics. His view of the dynamics of history leaves little room for the influence of "great individuals," and is more in keeping with the words of John Kenneth Galbraith quoted at the beginning of this chapter. It sees individuals as products of their time, having limited freedom to respond in the face of powerful forces. Kennedy's thesis, in essence, is this: The economic power of a nation naturally waxes and wanes. As times change, some nations are left clinging to power that their economic base can no longer support; others find new economic strength, and naturally seek greater influence. The inevitable result? Tension, which grows until something gives way. Usually the stress finds its release through armed conflict, after which the influence of each nation is brought back into rough balance with its true economic strength.

If this sounds at all like the processes at work in the Earth's crust, where stresses build up slowly to be released in sudden earthquakes, or in the sandpile game, where the slopes grow higher and more unstable until leveled again in some avalanche, it may be no coincidence. We shall see later that wars actually occur with the same statistical pattern as do earthquakes or avalanches in the sandpile game. Kennedy could find strong support for his thesis—as well as a more adequate language in which to describe it—in this theoretical idea. He may have been struggling to express in words, and in a historical context, what the concept of the critical state expresses mathematically.

Whatever lessons historians may be able to draw from all this, the meaning for the individual is more ambiguous. For if the world is organized into a critical state, or something much like it, then even the smallest forces can have tremendous effects. In our social and cultural networks, there can be no isolated act, for our world is designed—not by us, but by the forces of nature—so that even the tiniest of acts will be amplified and registered by the larger world. The individual, then, has power, and yet the nature of that power reflects a kind of irreducible existential predicament. If every individual act may ultimately have great consequences, those consequences are almost entirely unforeseeable. Out there right now on some red square in the field of history a grain may be about to fall. Someone trying to bring warring parties to terms may succeed, or may instead spark a conflagration. Someone trying to stir up conflict may usher in a lengthy term of peace. In our world, beginnings bear little relationship to endings, and Albert Camus was right: "All great deeds and all great thoughts have ridiculous beginnings."

One of the inevitable themes of our story is that if one wants to learn about the rhythms of history (or, shall we say, its disrhythms), one might just as well become familiar with the process by which, say, earthquakes happen. If the organization of upheaval and hypersensitivity is everywhere, one need not look far to find it. So let us leave human history and the individual aside for the moment, and first look to the simpler world of inanimate things. Let us go underground, into the dark, gritty world beneath the Earth's surface, and take a closer look at what goes on there. Surprisingly, in the underworld rumblings of our changeable planet, we shall encounter a way to understand the workings of a thousand things.

2

A Shaky Game

"Science" means simply the aggregate of all the recipes that are always successful. All the rest is literature.

—PAUL VALÉRY[1]

Since my first attachment to seismology, I have had a horror of [earthquake] predictions and predictors. Journalists and the general public rush to any suggestion of earthquake prediction like hogs toward a full trough.

—CHARLES RICHTER[2]